AFRL-SR-BL-TR-99-

REPORT DOCUMENTATION PAGE

00 54

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 1999	FINAL REPORT 15 Feb 97 - 14 Nov 98

4. TITLE AND SUBTITLE
MECHANICAL BEHAVIOR OF GRANULAR/PARTICULATE MEDIA
REINFORCED WITH FIBERS

5. FUNDING NUMBERS
F49620-97-1-0109

6. AUTHOR(S)
RADOSLW MICHALOWSKI

61102F
2302/CS

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
THE JOHNS HOPKINS UNIVERSITY
DEPARTMENT OF CIVIL ENGINEERING
3400 N. CHARLES STREET
BALTIMORE, MD 21218-2686

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFOSR)
801 N. RANDOLPH STREET, ROOM 732
ARLINGTON, VA 22203-1977

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE, DISTRIBUTION IS UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Fiber-reinforced ganular composits (for instance, fiber-reinforced sand) are considered as construction materials for such
applications as subgrades of airfields and roads, aircraft parking facilities, etc. An investigation into the mechanical behavior
of granular/particulate media with fibrous inclussions was carried out. This investigation was built on the results of a
previous study. Fiber-reinforced granular material was considered as a composite, and a mathematical homogenization
scheme was used to arrive at its macroscopic properties. The issues related to micrmechanic behavior, leading to anisotropy
and hardening/softening at the macroscopic level of description, were at the core of this investigation. This research
produced a material model which accurately describes the behavior of fiber-reinforced soils at failure. The research was
temianted before its conclusion, because of the elimination of the Particulate Mechanics program at the AFOSR.

14. SUBJECT TERMS			15. NUMBER OF PAGES
MECHANICAL FIBERS			6
			16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

Standard Form 298 (Rev. 2-89) (EG)
Prescribed by ANSI Std. 239.18
Designed using Perform Pro, WHS/DIOR, Oct 94

DTIC QUALITY INSPECTED 1

Final Report

submitted to

Air Force Office of Scientific Research

Directorate of Aerospace Studies
(Program: Particulate Materials)

Mechanical Behavior of Granular/Particulate Media Reinforced with Fibers

(Grant No. F49620-97-1-0109)

prepared by

Radoslaw L. Michalowski
(Principal Investigator)

Department of Civil Engineering
G.W.C. Whiting School of Engineering
The Johns Hopkins University

February 1999

Summary

Fiber-reinforced granular composites (for instance, fiber-reinforced sand) are considered as construction materials for such applications as subgrades of airfields and roads, aircraft parking facilities, etc. An investigation into the mechanical behavior of granular/particulate media with fibrous inclusions was carried out. This investigation was built on the results of a previous study.

Fiber-reinforced granular material was considered as a composite, and a mathematical homogenization scheme was used to arrive at its macroscopic properties. The issues related to micromechanic behavior, leading to anisotropy and hardening/softening at the macroscopic level of description, were at the core of this investigation. This research produced a material model which accurately describes the behavior of fiber-reinforced soils at failure. The research was terminated before its conclusion, because of the elimination of the Particulate Mechanics program at the AFOSR.

Objectives

The following were the objectives of this research: (a) progress in understanding of the elasto-plastic behavior of fibrous composites with a granular matrix, (b) identification of the most important mechanisms for fiber-matrix interaction (load transfer and distribution), (c) mathematical description of the elasto-plastic stress-strain behavior of the composite at the macroscopic level (homogenization of microstructural interactions), and a more general description of failure of anisotropic granular composites, and (d) collection of experimental evidence for validation of the mathematical description.

Accomplishments and New Findings

The first stage of the research concentrated mainly on the second objective (identification of the most important mechanisms for fiber-matrix interaction). The main results are described partly in papers listed in section: Publications. The research led to deriving of the analytic expressions for the failure criterion of isotropic fiber-reinforced granular materials, and to experimentally validating this criterion. The failure surface in the q, p, τ_{xy}-stress space [$q = (\sigma_x - \sigma_y)/2$, $p = (\sigma_x + \sigma_y)/2$] for the isotropic composite is shown in Fig. 1 (stresses are normalized by $\rho\sigma_0$, ρ - volumetric fiber content, σ_0 - fiber yield stress).
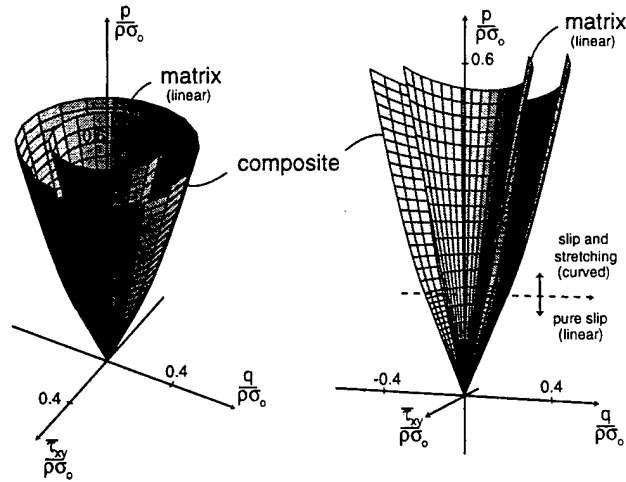
2

Figure 1. Failure surface for isotropic fiber-reinforced sand.

The mathematical description was extended to anisotropic soils. The process of composite homogenization is considerably more elaborate for an anisotropic distribution of fibers, but the calculations were carried out using a numerical optimization scheme, and the failure surface produced is shown in Fig. 2.
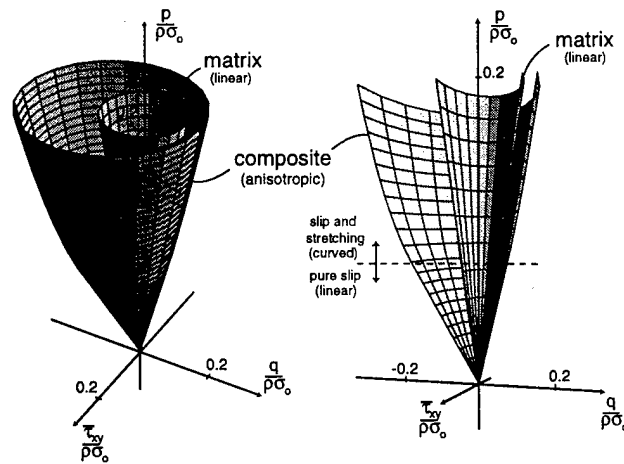

Figure 2. Failure surface for anisotropic fiber-reinforced sand.

Laboratory tests indicated a distinct kinematic (anisotropic) hardening effect. This effect can be described only approximately with the existing model. Preliminary results of calculations superimposed on the laboratory test results are shown in Fig. 3. More realistic mechanisms of

load transfer (from the matrix material to the fibers) need to be identified to obtain a better description, particularly in the early stages of the deformation process. Recent considerations revealed that a more elaborate hardening/softening law on the fiber-matrix interface needs to be used before the process of the composite strength mobilization can be captured. Other research issues identified as important are: instability of the fiber slip, scale effects caused by the nature of the stress-displacement law of fiber slip in addition to scale effects caused by the fiber aspect ratio, and influence of fiber stiffness on the behavior of the composite.
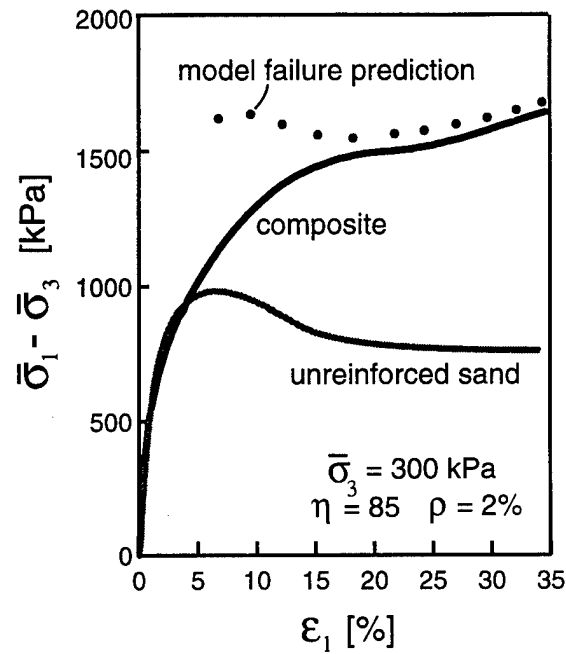
Figure 3. Kinematic hardening effect for fiber-reinforced sand. Comparison of a laboratory test with preliminary calculations.

In addition, a reinforcement with continuous filament was considered. The load transfer process in the latter case is similar to the *belt friction* effect, and such composite can be very effective. This type of composite was to be further explored in the last funding period. The two types of composites (fiber-reinforced and continuous filament-reinforced) are shown schematically in Fig. 4. An example of a cross-section of the yield condition for continuous filament-reinforced sand is presented in Fig. 5.
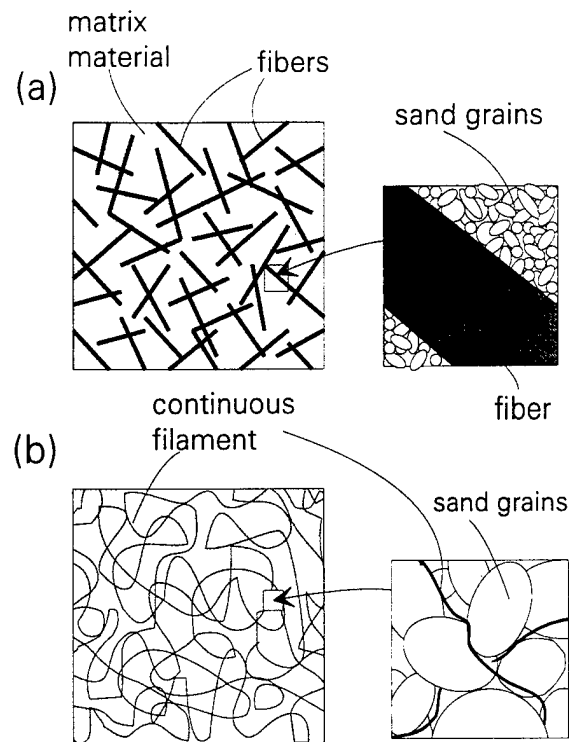
4

Figure 4. Reinforced granular composites:
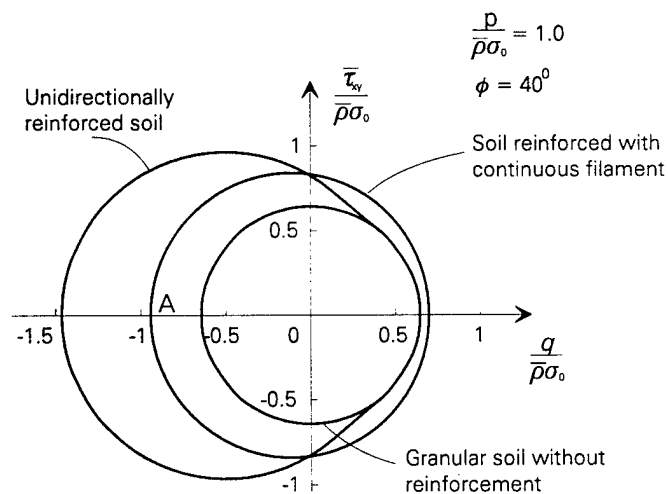(a) Fiber reinforcement, and (b) Continuous
thin filament.

Figure 5. Strength of filament-reinforced soil: Cross
section of the yield criterion.

Students Supported

There have been two students supported by this research project: Jan Čermák, who completed his Ph.D. dissertation in 1997 (thesis title: "Limit Behavior of Fiber-Reinforced Granular Soils"); and Liangzhi You, who is expected to complete his research toward his Ph.D. degree in 1999.

Publications

The main results are presented in the following papers:

Michalowski, R.L. and Čermák, J. (1997). *Anisotropic strength of fiber-reinforced soils*, Numerical Models in Geomechanics, S. Pietruszczak, G.N. Pande, eds., Proc. VI Intl. Symp., Montreal 2-4 July, 233-238.

Michalowski, R.L. (1997). *Mechanical behavior of granular/particulate media reinforced with fibers.* in: Selected Research in Particulate Materials and Shock Physics, Air Force Office of Scientific Research, 3-5 Feb., Landsdowne, VA, 65-68.

Čermák, J. and Michalowski, R.L. (1997). *Limit behavior of fiber-reinforced granular composites,* Mechanics of Deformation and Flow of Particulate Materials, C.S. Cheng, A. Misra, R.Y. Liang, M. Babic, eds., Proc. ASME Symposium, Evanston, June-July, 149-158.

Michalowski, R.L. (1998). *Kinematic hardening of fiber-reinforced granular composites.* In: Engineering Mechanics: A Force for the 21st. Century. Proc. of the 12th. Engineering Mechanics Conference (ASCE), La Jolla, May 1998, 1343-1346.

Michalowski, R.L. (1998). *Anisotropic Strength of reinforced soil.* Selected Research in Particulate Materials and Shock Physics, Air Force Office of Scientific Research, San Diego, May 1998.

Termination of the Project

This project was terminated in September 1998 due to elimination of the Particulate Mechanics program at AFOSR.